Semiconductor Based Transverse Bragg Resonance (TBR) Optical Amplifiers and Laser

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Prof. Amnon Yariv
California Institute of Technology, M/S 128-95,
1200 East California Boulevard, Pasadena, California 91125

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6. AUTHOR(S)
DR YARIV

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CALIFORNIA INSTITUTE OF TECHNOLOGY
1201 E CALIFORNIA BLVD
MAIL CODE 202-6
PASADENA CA 91125-0600

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
4015 WILSON BLVD
SUITE 713
ARLINGTON VA 22203
Dr Schlossberg

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13. ABSTRACT *(Maximum 200 words)*
We have fabricated electrically pumped, semiconductor TBR lasers in the InP/InGaAsP material system to demonstrate the efficiency gains possible by the incorporation of a transverse Bragg grating. By incorporating a transverse Bragg grating into a large-area laser, the optical modes of the laser can be designed to improve the efficiency compared to traditional index-guided lasers. The resulting transverse Bragg resonance (TBR) waveguide can be designed to have a single lateral mode that is distributed throughout the entire width of the laser for efficient, stable, single lateral mode operation even at high powers. In addition, by designing the dispersion of the TBR modes, we can increase the modal gain at the desired lasing frequencies for further efficiency improvements. We have finished some preliminary measurements of our laser samples and are currently working on optimizing the design for improved performance as well as more detailed measurement and characterization. Our initial findings indicate that the TSR laser may show efficiency gains compared to traditional broad-area lasers.

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1. Objectives

Our objective is to demonstrate and investigate the properties of semiconductor Transverse Bragg Resonance (TBR) optical amplifiers and lasers. (Unchanged)

2. Status of effort:

We have fabricated electrically pumped, semiconductor TBR lasers in the InP/InGaAsP material system to demonstrate the efficiency gains possible by the incorporation of a transverse Bragg grating. By incorporating a transverse Bragg grating into a large-area laser, the optical modes of the laser can be designed to improve the efficiency compared to traditional index-guided lasers. The resulting transverse Bragg resonance (TBR) waveguide can be designed to have a single lateral mode that is distributed throughout the entire width of the laser for efficient, stable, single lateral mode operation even at high powers. In addition, by designing the dispersion of the TBR modes, we can increase the modal gain at the desired lasing frequencies for further efficiency improvements. We have finished some preliminary measurements of our laser samples and are currently working on optimizing the design for improved performance as well as more detailed measurement and characterization. Our initial findings indicate that the TBR laser may show efficiency gains compared to traditional broad-area lasers. We are also pursuing work to control the longitudinal mode by incorporating a second grating in the longitudinal direction. This will provide us a greater degree of control over the optical mode enabling the possibility of truly single-mode (both in spatial modes and frequency modes) lasers.

3. Accomplishments/New Findings:

1. Theoretical Work

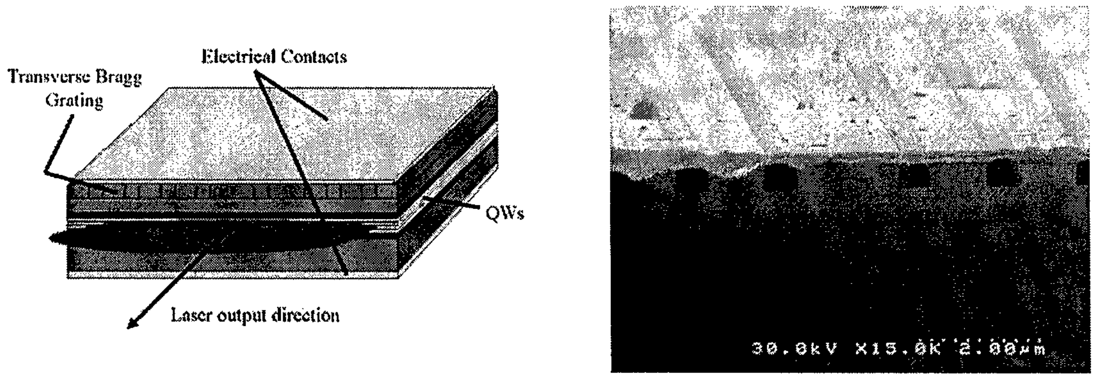
From an analysis of the modal field distribution, we have defined an effective modal width resulting from the substantial penetration of the field into the cladding region. This effective modal width is solely determined by the reflection of the transverse Bragg grating (κ in the coupled mode formalism), and thus, the transverse modal width of a single-mode laser can be considered a free parameter by appropriately designing the transverse Bragg grating. For an example design, the effective modal width of a single-mode TBR laser was found to approach 100μm, or ≈20 times larger than single-ridge waveguide semiconductor lasers.

Another advantage we have found for the TBR waveguide is the unique dependence of the propagation loss on the transverse mode. This modal loss discrimination can lead to a quasi-single-mode operation with an effective transverse modal width even greater than that calculated for the true single-mode TBR waveguide. Using the concept of mode suppression ratio (MSR), it was shown that for a 20dB MSR, the effective transverse modal width for quasi-single-mode operation can reach 300μm.

From our numerical simulation work (2D FDTD), we have verified our previous analytical, coupled-mode models predicting discrete core widths are necessary for low loss propagation and found good quantitative agreement. This study leads us to conclude that the TBR waveguide can be treated as an entirely new class of waveguide due to the significant field penetration into the cladding.

We have found the guiding within a TBR waveguide results in a cavity folding effect that produce an increased gain per unit length in the longitudinal, propagation direction. In a laser, this gain enhancement may lead to more efficient operation and higher powers compared to traditional semiconductor lasers of the same size. The physics of the gain enhancement can also be applied for modulation purposes. A TBR device taking advantage of this enhancement can either be made shorter in the longitudinal direction for the same modulation depth, as in a directional coupler modulator, or the modulation can be made more efficient within a fixed size device, as in an electro-optic modulator.

2. Fabrication process



(a) (b)

Figure 1. (a) Schematic of a TBR laser. (b) SEM image of an InP/InGaAsP TBR laser showing the surface grating with the central defect guiding region and the p-side electrical contact.

A schematic drawing of a TBR laser incorporating a surface grating is shown in Fig. 1a. The TBR laser is fabricated by e-beam lithography on a commercially grown InP epitaxial wafer with 4 InGaAsP quantum wells with a peak luminescence around 1540 nm. The active region is covered by 170 nm of InGaAsP followed by 400 nm of InP that is used to form the surface grating. This is capped with 5 nm of InGaAs. The grating is transferred with a two step wet etch of diluted $HBr:HNO_3$ and HCl acids. A BCB (Cyclotene 3022-46) planarization layer is applied to bridge the gaps between the grating ridges and etched back with an O_2/NF_3 inductively coupled plasma reactive ion etch (ICP-RIE) followed by thermal evaporation of p-type electrical contacts, AuZn/Au. After mechanical lapping, the n-type contacts, AuGe/Au, are applied and bars are cleaved. A cross section of a finished device is shown in Fig. 1b.

3. Electrically pumped TBR lasing showing preliminary evidence of efficiency gains

The TBR laser was designed to be 100 μm wide with a grating pitch of 1.5 μm. The tested bars were cleaved to a length of 554 μm. The grating pitch was chosen so that the angle of incidence at the facets would be less than the critical angle to prevent total internal reflection. At this grating pitch, all wavelengths within the gain spectrum should be able to couple light out.

The lasers were tested in pulsed mode with no active cooling to minimize heating effects. Pulse settings were 50 ns pulses and a 40 μs period. The light-peak current density curves are shown in Fig. 2. The TBR threshold current density was measured to be 446 A/cm^2 and the broad area threshold current density was measured to be 718 A/cm^2, corresponding to a 38% reduction of the threshold current density. Since the lasers being compared have different lengths, we need to consider the effect of length on threshold current density [1].

The threshold current density can be approximated as:

$$J_{th} \approx qM \exp[2(\alpha_i + \alpha_m)/(\Gamma g_0)] \qquad (1)$$

where q is the electron charge, M is a material parameter describing the internal quantum efficiency and factors affecting the transparency carrier density, α_i the average internal loss , α_m the mirror losses, Γ the confinement factor, and g_0 a normalizing gain constant.

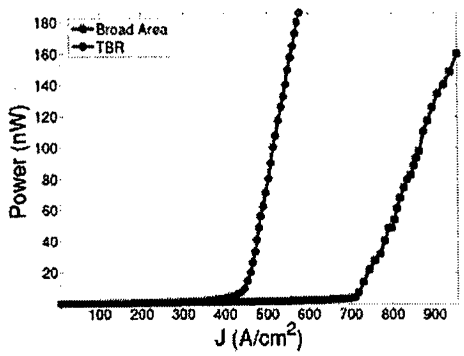


Figure 2. Light vs. peak current density curve of the broad area laser and the TBR laser. The TBR laser has a threshold current density about 38% less while being about 15% shorter and twice as wide.

Since the lasers are fabricated from the same wafer material with the same quantum wells and the same vertical confinement, we assume that M, α_i, Γ, and g_0 are reasonably equivalent. Then, the only term that is dependent on the length is α_m, the mirror losses. For a symmetric device (the 2 facets are the same),

$$\alpha_m = (1/L)\ \ln(1/R) \qquad (2)$$

defines the length dependence. As L increase, α_m decreases and reducing the mirror loss term should decrease the threshold current density. In other words, as the length increases, the mirror loss contribution becomes less dominant compared to the internal loss term. Thus, we would expect that a slightly longer device will have a lower threshold. Since the broad area laser is 100 μm longer, cutting it shorter or making the TBR longer would only make the threshold difference larger.

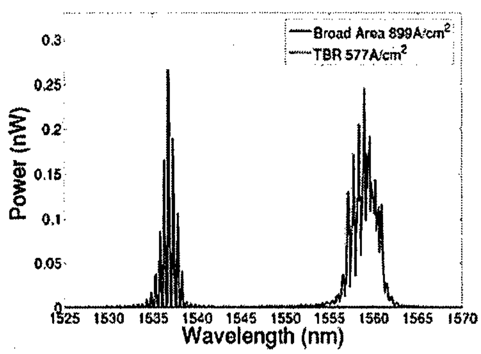


Figure 3. Lasing spectra of the broad area laser and the TBR laser at similar peak output power levels. The TBR laser is red-shifted about 22 nm although it is fabricated from the same wafer material as the broad area laser.

Fig. 3 shows the lasing spectra of the two devices for similar power levels. Since the transverse Bragg grating does not affect the longitudinal modes of the laser, there is no frequency selection beyond the Fabry-Perot resonances due to the facet reflections. The peak lasing wavelength of the broad area laser is approximately 1537 nm while the TBR lases at approximately 1559 nm. This 22 nm red shift of the peak lasing wavelength is also apparent on other TBR devices of the same grating design from the same wafer as compared to other broad area lasers also from the same wafer. Thus we conclude that the spectral shift may be a result of the TBR structure, but possibly due to resistive heating effects rather than the optical mode design. Further evidence of this is seen in the near-field image showing the modal structure (see below).

4. Modal structure

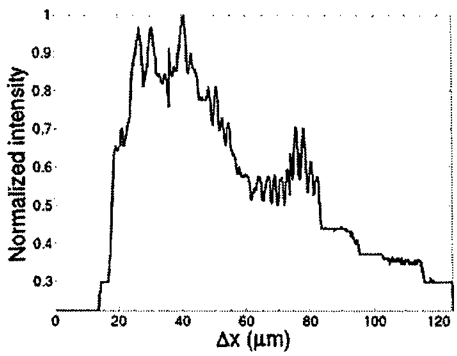


Figure 4. Near field intensity distribution of the TBR laser. The peak intensity on the left corresponds to the electrical contact pad where current is applied through a probe tip.

Fig. 4 shows the near-field intensity distribution as captured with a Vidicon infrared camera. The period of the intensity modulation is approximately 1.8 μm. This roughly corresponds to the grating pitch and provides evidence that the TBR laser is lasing in a high order mode with fast oscillations on the order of the grating pitch. The left of the profile, $\Delta x \sim 0$ μm, corresponds to a contact pad at the edge of the TBR laser where a probe was applied. The intensity gradient, with greatest intensity near the contact pad, suggests there is a large inhomogeneity in the current distribution across the laser indicating the contacts may have poor conductivity.

Our findings thus far show that lasers based on TBR waveguides have the potential for controlling the lateral modes of a large area laser, limiting it to a single transverse mode and increasing efficiency by providing a larger modal gain. An electrically pumped TBR laser based on an InP/InGaAsP material system was demonstrated in pulsed operation. Compared to a gain-guided broad area laser, the TBR laser showed a reduced threshold current density (about 38% less), suggesting that significant efficiency improvements may be possible. However, the contacts may have high resistance leading to heating and poor current distribution. While these features are nonideal, the TBR laser shows promise meriting further investigation for application to high power, high efficiency, large-area lasers.

5. Longitudinal mode control for TBR lasers

A TBR laser has multiple longitudinal modes because the longitudinal feedback mechanism is provided by the Fabry-Perot resonances from the reflection at the end facets. We design a two dimensional Bragg grating (2DBG) structure with two quarter-wave slip line defects to control the optical modes in both longitudinal and transverse directions by incorporating a longitudinal Bragg grating into a TBR waveguide. The resulting 2DBG laser makes single transverse and longitudinal mode operation possible through the proper design of the gratings and defects. Unlike conventional two dimensional photonic crystal lasers, which use a large refractive index perturbation to confine light in a plane, the 2DBG structures described here selectively control longitudinal and transverse wavevector components using a weak index perturbation. Thus, the optical modes confined by the grating in a 2DBG laser will spread out into the periodic active medium, allowing for high power operation.

Figure 5 shows a schematic of a typical structure of a 2DBG laser. The laser consists of a rectangle lattice array of air holes with two line defects in a thin slab, which includes active multiple-quantum-well layers. In the limit of weak index perturbation, which obtains for example for sufficiently small hole diameter, the optical mode for the proposed structure can be separated into transverse (x), vertical (y), and longitudinal (z) components. In the wafer plane (x-z), a mode that satisfies both transverse and longitudinal Bragg resonance conditions will be confined due to the distributed Bragg reflection. Light that does not satisfy the Bragg conditions will be lost. This Bragg condition can be expressed as:

$$k_x = l\frac{\pi}{a}, k_z = j\frac{\pi}{b} \quad (l \neq 0, j \neq 0),$$

where k_x is the transverse wavevector, k_z is the longitudinal wavevector, a is the transverse grating period, b is the longitudinal grating period, and l, j are the orders of the grating. Because the vertical wavevector k_y is determined by the wafer epitaxial layer structure, k_x and k_z satisfy:

$$k_x^2 + k_z^2 = n_{eff}^2 k_0^2,$$

where n_{eff} is the effective refractive index for the optical mode of the wafer structure. In our design, we chose $k_z \approx n_{eff} k_0$. Two line defects perpendicular to each other are introduced in the 2DBG to define the optical resonance condition in the longitudinal and transverse directions. Thus, the widths of two line defects should satisfy [1, 2]:

$$W_1 = (2m+1)a/2l, W_2 = (2n+1)b/2j,$$

Where W_1 is the transverse defect width, W_2 is the longitudinal defect width, and m, n are integers (see Fig. 5).

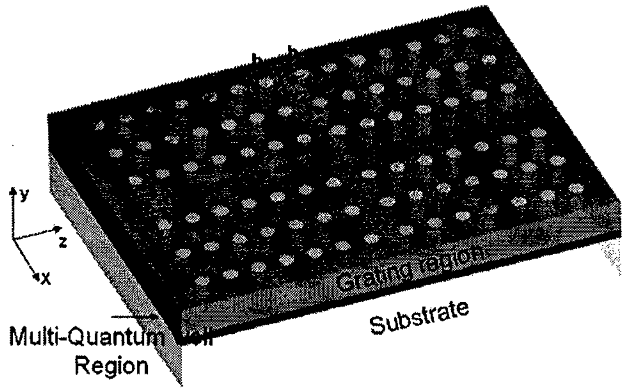


Figure 5. An illustration of a two dimensional Bragg grating laser with two line defects. a is the transverse grating period, b is the longitudinal grating period, W_1 is the transverse defect width, and W_2 is the longitudinal defect width

We are currently working on the fabrication and measurement of those devices.

References:

[1] L.A. Coldren, and S.W. Corzine, "Diode lasers and photonic integrated circuits," (J. Wiley & Sons, Inc., New York, NY, 1995) pp45-46.

4. Personnel Supported (Dec. 2003-Nov. 2005):

Personnel	Type
Yariv, Amnon	Professorial Faculty
Cooper, Kevin M.	Bi-Weekly Research Staff
Ghaffari, Alireza	Bi-Weekly Research Staff
Huang, Yanyi	Postdoctoral Scholar
Choi, John Myun	Grad Assistantship
Green, William Michael John	Grad Assistantship
Sun, Xiankai	Grad Assistantship

5. Publications Dec. 2003 - Nov. 2005

1. W. Liang, Y. Xu, J.M. Choi, and A. Yariv, "Engineering transverse Bragg resonance waveguides for large modal volume lasers," Opt. Lett., **28** (21), 2079-2081 (2003).
2. J. M. Choi, W. Liang, Y. Xu, and A. Yariv, "Loss optimization of transverse Bragg resonance waveguides," J. Opt. Soc. Am. **21** (3), 426-429 (2004).
3. W. Liang, Y. Xu, J.M. Choi, A. Yariv, and W. Ng, "Transverse Bragg-resonant enhancement of modulation and switching," IEEE Photon. Technol. Lett. **16** (10) 2236-2238 (2004).

6. Interactions/Transistions

a. Participation/presentations at meetings, conferences, seminars, etc.:

J.M. Choi, L. Zhu, W.M.J. Green, G. DeRose, and A. Yariv, "Large-area, semiconductor transverse Bragg resonance (TBR) lasers for efficient, high power operation," submitted to ICALEO 2005. (Oct. 30 - Nov. 3)

b. Consultative and advisory functions to other laboratories and agencies: None.

c. Transitions: None.

7. New discoveries, inventions, patent disclosures
US Patent #6,934,425 Issued: 8/23/2005
Transverse Bragg Resonance Lasers and Amplifiers and Method of Operating the Same
Inventors: Yariv, Amnon

Canada Patent Serial #2513214, filed
Transverse Bragg Resonance Lasers and Amplifiers and Method of Operating the Same
Inventors: Yariv, Amnon

Europe Patent Serial #04704931.7, filed
Transverse Bragg Resonance Lasers and Amplifiers and Method of Operating the Same
Inventors: Yariv, Amnon

8. Honors/Awards
Prof. Yariv is a member of the American Physical Society, Phi Beta Kappa, the American Academy of Arts and Sciences, the National Academy of Engineering, the National Academy of Sciences, a Fellow of the Institute of Electrical and Electronics Engineers and the Optical Society of America. He was the recipient of the 1980 Quantum Electronics Award of the IEEE, the 1985 University of Pennsylvania Pender Award, the 1986 Optical Society of America Ives Medal, the 1992 Harvey Prize, the 1998 OSA Beller Medal and received an Honorary Doctorate, December 2000 from Ben Gurion University of the Negev, Israel